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April 2, 2019

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Mr. Martin Pfeiffer
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Dear Mr. Pfeiffer:

FREEDOM OF INFORMATION ACT REQUEST ORO-2019-00474-F

This letter and the enclosure complete our response to your January 15, 2019, Freedom of Information Act (FOIA) request for copies of "any and all reports and planning documents discussing efforts to assess or model the climate impacts of nuclear war and the results of any such efforts. You may restrict your search to the time period between and including January 1, 1982 to January 1, 2019." Your request was transferred to the U.S. Department of Energy (DOE) Oak Ridge Office (ORO) from the DOE Headquarters FOIA Office and received for processing at ORO on February 14, 2019.

The enclosed report prepared by the Oak Ridge National Laboratory is the only document found at DOE/ORO in response to your request. Searches were also conducted at the Pacific Northwest National Laboratory, Thomas Jefferson National Accelerator Facility, and SLAC National Accelerator Laboratory, which are also under the jurisdiction of the DOE/ORO; however, no records were found at any of those sites.

If you have any questions about the processing of your request or this letter, you may contact me by telephone at (865) 576-2129, by e-mail at Linda.Chapman@Science.Doe.Gov, or by writing to the address on the top of this letter. I appreciate the opportunity to assist you with this matter. There is no charge for processing this request.

Sincerely,

Linda M. Chapman
Linda G. Chapman
FOIA Officer

Enclosure

A PRELIMINARY REVIEW OF THE TTAPS
NUCLEAR WINTER SCENARIOS

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A. M. Perry

Emergency Technology Program
Energy Division

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The paper by Turco, Toon, Ackerman, Pollock & Sagan (TTAPS) on Nuclear Winter was reviewed. The possibility of climate upset must be taken seriously but the uncertainties are larger than the postulated effects. The effects if real would fall more heavily on the Soviet Union than on the U.S. and would provide incentive for smaller, more accurate weapons, avoiding cities, and earth-penetrating weapons.		

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A Preliminary Review of the TTAPS
Nuclear Winter Scenarios
C. V. Chester, F. C. Kornegay and A. M. Perry
Oak Ridge National Laboratory

We have attempted a brief review of the uncertainties in the paper "Global Atmospheric Consequences of Nuclear War" by Turco, Toon, Ackerman, Pollack & Sagan on nuclear winter (hereinafter called the TTAPS study) (Turco, et al. 1983^a.)

In performing this review, we have had access to their earlier and lengthier paper that was circulated in draft form in March, 1983 (Turco, et al. 1983^b.) The revision of that paper (Reference 15 of the TTAPS Science article) has, to our knowledge, not been completed yet. These longer papers contain many details that were not possible to include in the Science paper, and we found the March 1983 draft to be very helpful. We did not have access to the (unpublished) report of the National Academy of Sciences. We have not conferred with any of the TTAPS authors.

The TTAPS authors are distinguished scientists with impressive publication records and excellent reputations in their field, the study of planetary atmospheres. The TTAPS authors appear to have made a careful and thorough effort, using the best available information, to estimate the consequences of the injection of large amounts of smoke and dust into the atmosphere from the explosions of a nuclear war. Where data exist they have used the best we know about. Where hard pertinent data do not exist (the more common case) they have made estimates and carried out parametric variations of their calculations around their estimates.

However, even using the best available data, enormous uncertainties exist in the final results of the calculations. We think it can now be believed with some assurance that a relatively large nuclear war will result in some climate changes which will include some cooling of at least the northern hemisphere. However, the magnitude and duration of the cooling are subject to very large uncertainties. These are discussed below in the section titled "Uncertainties."

The cumulative effect of all the uncertainties is difficult to evaluate quantitatively. In our judgment, it is more likely that the initial cooling will be smaller than the TTAPS estimate (for their baseline case) rather than larger. But we do not think, for example, that the sign of the effect is wrong, i.e., that such large quantities of soot and dust would cause a warming rather than a cooling of the surface. It is also entirely possible that the recovery could be slower than indicated by TTAPS, so that significant temperature reductions (e.g., 5°C or more) could persist well into a second year. This raises the possibility of serious reductions in food production for two consecutive years.

It is easy to be preoccupied with the magnitude of the initial cooling, which is certainly the most arresting feature of the TTAPS scenarios. Certainly it is important to know whether the average temperature would fall to -25°C or only to -5°C (a factor of two in the temperature decrease). In either case, the effects would be very severe. But it may be equally important to know whether temperatures may remain more than 5°C below normal for as much as two years.

SOME GENERAL OBSERVATIONS

The earth's atmosphere when clear is nearly transparent to light in the visible range of wavelengths as emitted by the sun, but nearly opaque in some wavelength intervals to infrared radiation emitted by the earth (owing primarily to absorption in carbon dioxide, water vapor and ozone). Clouds cover approximately 50% of the earth's surface at any time. Absorption and reflection of sunlight by the atmosphere (mainly by clouds) each accounts for about one-fourth of the incident sunlight; the remaining one-half reaches the surface, and most of that is absorbed there.

If the earth had no atmosphere or had an atmosphere completely opaque to visible and infrared radiation and maintained the present reflectivity or albedo, in order to balance the solar energy absorbed by the earth, either the bare surface or the top of an opaque atmosphere would have to have a temperature of approximately 255°K (-18°C, 0°F).

Because the present atmosphere is nearly transparent to visible light and somewhat opaque to infrared radiation, it is possible for the surface to be warmer than the effective radiating temperature of the whole system, i.e., 288°K instead of 255°K. This is sometimes called the "greenhouse effect."

Injecting large amounts of dust or smoke into the atmosphere can substantially alter earth's albedo and can eliminate the "greenhouse effect" by causing the absorption of most of the incoming solar energy high in the atmosphere. Deprived of the heat source at the surface and in the lower atmosphere, the earth's surface and the atmosphere underneath the absorbing layer will assume approximately the same temperature as the radiating aerosol layer, 255°K if the albedo is unchanged, or less if the albedo is increased.

It is believed that this phenomenon has in fact occurred in the past as a result of very large volcanic eruptions (much larger than any within recorded history) and asteroid impacts. The best documented such event was 65 million years ago, and is referred to as the Cretaceous-Tertiary event. (Alvarez et al, 1980). Paleontological evidence indicates wholesale extinction of living species associated with these events, implying massive changes in the environment for some finite periods of time. The authors of the present study hypothesize that the smoke and dust from a nuclear war could produce comparable effects on the environment, in particular severe cooling of the earth's surface for several months to a year.

In their study, the TTAPS authors postulated a wide range of nuclear attacks from 100 megatons to 25,000 megatons with a variety of numbers of warheads, yields, burst heights, targets, smoke production and dust production. Their "baseline" exchange in their Science paper is a 5,000 megaton attack with 57% of the yield in surface bursts; 20% of the yield is expended on urban or industrial targets. A total of 10,400 explosions was postulated. The "baseline" exchange is estimated to cause a reduction in average surface temperature in the northern hemisphere of approximately 40 centigrade degrees; this occurs approximately 30 days after the attack, followed by a re-warming over the ensuing year to within a few degrees of the pre-attack temperature.

The effects are generally more severe as the size of the attack increases and assumptions regarding some key parameters become more pessimistic, i.e., more smoke and dust per MT weapon yield, smaller particle sizes and longer removal times. In general, they find that even relatively small attacks can produce significant cooling. Smoke, particularly from urban fires, due to its much higher light-absorbing capability, is dominant in the initial cooling, although dust from surface bursts not in urban areas can produce significant climate change.

UNCERTAINTIES

Fire and Smoke

There are significant uncertainties in the estimation of the quantities of smoke produced by the various weapon-induced fires, and we think this may be one of the larger sources of uncertainty in the overall analysis. We also think that the actual smoke production, in the specified scenarios, is more likely to be smaller than the TTAPS estimate than to be larger. The major uncertainties, in our view, relate to the fuel loading in cities, the area ignited by weapons, the fraction of fuel burned, the rate of burning, the smoke emission factors, and the probability that mass fires or fire storms would be produced.

There is some question as to whether the TTAPS authors have considered the much larger proportion of masonry construction materials in many if not most cities of the world today, as compared with that which was used in the construction of pre-war Hiroshima and Nagasaki. There also seems to be no consideration of the effects of blast damage of cities on their combustibility. A city which has been blown flat by the blast from multiple nuclear weapon explosions is more likely to burn as isolated small fires or smoldering fires than as the conflagrations that occurred in cities which are largely standing such as Dresden and Hamburg, during World War II. The effects of masonry rubble would not only reduce the quantity of material available for combustion, but would reduce the height at which the smoke from such combustion is injected into the troposphere. If confined to the planetary boundary layer under

1500 meters altitude, such smoke would be more rapidly removed by dry deposition, as well as rainfall, than if it were injected in the upper troposphere as from a large conflagration.

Furthermore, smoke lying in the first 1500 meters of the atmosphere would produce a smaller temperature reduction than if the smoke were at 5 to 7 km, where most of the smoke in the TTAPS analysis is assumed to stabilize. This is true because most of the atmosphere would still be above the low smoke layer, and something like the normal lapse rate would still apply over most of its normal range. Of course, such a smoke layer also reduces the already-small surface albedo and thus makes a positive contribution of perhaps (+) 3-4°C to the net temperature change.

The TTAPS authors do not appear to have done any detailed target analysis and attack analysis. Instead they have adopted broad averages for the properties of the targets in terms of quantity of combustible material. Similarly, for convenience and ease of computation, they have simplified the array of weapon yields into a few categories. Their broad assumptions seem reasonable but do not explicitly treat facts such as the location of U.S. missile silos in areas of very little combustible fuel or the relatively small size of U.S. warheads that would be targeted on Soviet counterforce targets. They do not seem to recognize that most U.S. cities are surrounded by cleared land rather than forests. For these reasons we believe that their estimates of smoke from both wildfires and urban fires are much too high.

Dust

Large amounts of fine dust are injected into the stratosphere by surface bursts of weapons in the megaton range. Weapons below 100 kilotons do not loft dust into the stratosphere. Stratospheric dust is important since removal processes are slow and this dust is responsible for more of the longer term effects.

The TTAPS authors have used the best available information regarding both the quantities of dust produced by surface bursts and the particle size distributions. These data come from the Pacific megaton-range tests and some low-yield tests at the Nevada Test Site. It is not known how dust properties would change for megaton weapons

exploded on surfaces other than coral.

Dust production per megaton of yield is markedly reduced as the burst height of the weapon increases. There is an extremely large uncertainty in the fraction of nuclear weapons that would be exploded on contact as opposed to the number that would be exploded as low airbursts or at optimum burst heights for some overpressure. Such information is normally held in the highest security classifications by the U.S. and the Soviet Union as is intelligence information obtained by either side about the other's practices. Furthermore, fuse settings of any ordnance are normally adjustable and the same could be reasonably expected for nuclear weapons. The practices of today could very easily change tomorrow.

Behavior of the Perturbed Atmosphere

One of the largest sources of uncertainty in estimating the intensity and duration of the expected cooling is surely the behavior of the highly altered atmosphere.

The earth-atmosphere climate system is highly non-linear. If indeed the quantities of dust and soot were so large that much of the incident solar radiation were deposited high in the atmosphere, atmospheric circulation patterns would surely be much altered. Convective activity in the lower atmosphere would be greatly reduced over the cold land masses but might be enhanced over the oceans. Precipitation might be markedly reduced, at least over the continents, although it might be increased over the oceans. The residence times for soot, governed by precipitation, could be very different than we assume on the basis of present atmospheric behavior. In particular, they could be longer, although the possibility must be acknowledged that aerosols could be washed out rapidly from the lower atmosphere over the oceans.

Certainly the interactions between the troposphere and the stratosphere could be markedly altered. Indeed, these regions, as customarily defined, would hardly be recognizable, at least in the mid-latitudes of the Northern Hemisphere. The residence time of dust in the middle atmosphere, e.g., between 12 km and 30 km altitude, could be quite different, possibly longer, than that of small amounts of dust in the present stratosphere.

Stephen Schneider and his co-workers at the National Center for Atmospheric Research have carried out calculations using a General Circulation Model which illustrates dramatic change (Covey et al, 1983) in the circulation patterns caused by the injection of smoke from a nuclear war. However, their model contained no smoke removal mechanism.

Dispersion

It has been said that the assumption of instantaneous dispersion of dust and soot over the entire Northern Hemisphere is highly unrealistic, implying that this is a major weakness of the TTAPS study. While the spreading of any one cloud over the whole hemisphere within a few days is of course unrealistic, it is not apparent to us that the simplifying assumption of uniform cloud distribution is inappropriate in the present case, or that it is necessarily a source of large error in the analysis. Nor is it obvious, a priori, that the real case would be less severe than the hypothetical uniform case. Our reasoning is as follows. First of all, we are dealing with a very large number of source points which are spread out mainly over the northern continental land masses, roughly between latitudes 30°N and 60°N , or possibly 20° to 60°N . Smoke production from urban fires will be spread out over several hours. Over the major target areas (e.g., the U.S., western Europe, portions of the Soviet Union), it seems reasonable to us that the clouds will spread and merge in a few days. The horizontal spreading rates assumed by TTAPS seem reasonable to us. Present global circulation times for tropospheric air masses in mid-latitudes can be as little as 12 days. Clouds from U.S. targets could reach Europe in 3-5 days, merging with the tail of the European cloud. Clouds from targets in Eastern Asia could reach the U.S. in less than a week. Nevertheless, the travel time for a single global circuit is on the order of the e-folding time for normal lower tropospheric washout, so complete uniformity is unlikely to be achieved.

North-south spreading may be less rapid than east-west spreading. Thus, for a few weeks, the clouds may remain predominantly in the latitude band of origin, i.e., 30°N - 60°N , and may be two or three times

thicker, on the average, than if they were spread out over the whole hemisphere. If the major tropical circulation cells are not immediately disrupted, there may not be much relief for the middle latitudes from the warmer tropics during the period of greatest cooling.

We have considered the effect of nonuniformity or "patchiness" in the cloud cover by postulating various distributions of optical thickness for a given average thickness. That is, if t_i is the optical depth over a fraction W_i of the total area and \bar{t} is the average optical depth over the entire area, we require that $\sum_i W_i t_i = \bar{t}$ and calculate the average energy flux at the surface as

$$\bar{P} = \sum_i W_i e^{-t_i}$$

We do this for various distributions $t_i(W_i)$ and for various values of the average optical thickness, \bar{t} .

In performing these numerical experiments, we considered: (1) cases with various percentages of clear area, the balance being covered by a cloud of uniform thickness somewhat greater than the average; (2) step-wise fractional areas with various percentages of the average thickness; (3) uniform variations of thickness between a minimum value (including zero) and a maximum value (including twice the average thickness); (4) non-linear (power-law) variations such that most of the cloud has close to the average thickness with small fractional areas having either very thin or very thick cloud cover.

A useful way to express the results is to determine the thickness of an equivalent uniform layer that would transmit the same amount of solar energy as the non-uniform layer of specified average thickness. We found, for a wide range of plausible non-uniform distributions, that the equivalent uniform layer has a thickness at least one-third to one-half the average thickness of the non-uniform layer, for average optical thickness up to 5. That is, the non-uniformities we considered are equivalent to reducing the quantity of soot in a uniform layer by a factor of at most 2 or 3, and often less. For average thicknesses $t = 2$ or 3, the reduction factors are closer to 1. We conclude that the reduced attenuation of sunlight for a non-uniform smoke distribution, as compared with a uniform one, may well be offset by limited north-south

spreading, giving a greater optical thickness in mid-latitude, than if the smoke spread uniformly over the hemisphere. It should be said that we did not consider percentages of clear area as high as 50%, thinking that case rather unlikely. (Normal cloud cover averages about 50%.) The highest clear area we considered was 20%.

Residence Time

The assumptions made by TTAPS with respect to the residence time of tropospheric aerosols seem very reasonable to us, to the extent that present atmospheric processes remain applicable. A time constant of 10 days for removal of particles in the lowest layers of the atmosphere and of 20 days for altitudes of 5-7 km are consistent with the behavior of the unperturbed atmosphere. The slow rainout case analyzed by TTAPS in sensitivity studies (a threefold increase in these time-constants), though perhaps designed to explore the effect of uncertainties in behavior of the present atmosphere, may also be viewed as a test of the effect of possible alterations in the atmosphere arising from the disturbance. With that purpose in mind, it is difficult to say whether a threefold increase in residence time is sufficient or not.

With respect to the removal rate of stratospheric dust, apart from the questions raised above regarding the effect of major changes in atmospheric circulations, we are much intrigued by differences in removal rates obtained by TTAPS in the present study (of Nuclear Winter) and in a study by four of the same authors regarding the so-called Cretaceous-Tertiary extinction event (KT event) (Pollack 1983.) In that event (about 65 million years ago) an asteroid is believed to have struck the earth, the impact dispersing some 5×10^{15} kg of dust into the stratosphere. This is 5000 times as much dust as in the TTAPS baseline Nuclear Winter scenario, although the minimum temperatures calculated in the two events are not very different. The removal rates (for stratospheric dust) that were estimated by Pollack et al. for the KT event are 10 times greater than those obtained by TTAPS for the Nuclear Winter scenario. This is attributed to coagulation of fine particles into larger particles which then settle out under gravity, the dominant removal mechanism in that case. This process is neglected in

the Nuclear Winter analyses. This difference in treatment may well be justified by the much higher initial concentration of dust particles in the KT event. However, the higher removal rates for the KT event are assumed to continue as the dust concentration drops by several orders of magnitude. This assumption appears inconsistent with the Nuclear Winter scenario.

One-Dimensional Model

The TTAPS authors' one-dimensional climate model simply calculates radiative and convective heat and mass transfer in the atmospheric column, assuming that the results are representative of average conditions over all the land areas of the hemisphere. (A separate computation is done for the oceans and shows, as expected, very much smaller temperature reduction, because of the enormous heat capacity of the oceans.)

Much is lost by this simplification. First, the exchange of heat between the oceans and the continents can significantly decrease the temperature reduction over the land, at least in areas near the coasts. The TTAPS article estimates that at most a 30% reduction in the magnitude of the cooling over the continents could be realized from this transport of heat.

The presence of a relatively warm ocean and a very cold continent will probably result in strong storms at the coast. Cold air descending over the continents, flowing to the coast, mixing with water vapor, and rising to form rainfall, could possibly result in hurricane-like storms. If the storms are frequent enough and large enough in area, they could contribute greatly toward the removal of the smoke and dust particles from the troposphere.

Such questions could be studied with available three-dimensional, general circulation models. As mentioned previously Stephen Schneider and his co-workers at the National Center for Atmospheric Research, have done this. They used a general circulation model with a resolution of 4.5° latitude, 7.5° longitude, and 9 layers in the atmosphere. There was no aerosol removal mechanism. They assumed that 2×10^{14} g. of smoke was injected instantaneously and remained fixed for the 20 days

that the simulation ran, forcing absorption of all the sunlight in the middle troposphere. The aerosol was assumed transparent to infrared radiation.

Substantial cooling was observed in 2 days with temperatures over the interiors of the continents reaching levels consistent with the TTAPS study. Cross-equatorial circulation was greatly enhanced especially in the spring and summer.

The authors recognize that "there is a need for fully interactive self-consistent aerosol transport and removal calculations" (Covey, et al 1983).

Other Feedbacks

We have already referred to the highly non-linear behavior of the earth-atmosphere climate system in its response to various perturbations. Studies of other, much smaller perturbations - including various aerosols and minor gaseous constituents such as CO₂ - have shown the importance of numerous, often subtle, changes in the climate system as it adjusts to the initial disturbance. One familiar example is change in atmospheric moisture content, perhaps keeping the relative humidity nearly constant. (It appears that this change is taken into account in the TTAPS analysis.) Another effect, recognized but not evaluated in the present context, is the effect of the added smoke particles on the nucleation of raindrops. It has been observed, in smoke from forest fires, that the very large number of small particles, known as Aitken nuclei, may "tie up" water in numerous small droplets, making rainfall less likely to occur.

Undoubtedly, many such feedback mechanisms will be recognized in further analysis of the "Nuclear Winter" phenomenon. Their cumulative effect, though not known at present, could be substantial.

TEST FOR OVERALL REASONABLENESS

The TTAPS paper proposes a set of consequences of nuclear attack which are qualitatively different from those of most previous studies of the effects of nuclear war mainly because of the large quantities of smoke and dust that are at the focus of the TTAPS study but not included (or only crudely evaluated) in most previous studies. While the

individual assumptions in the study are in reasonable ranges, the authors themselves point out that the overall uncertainties are quite large. One is led to search for some empirical evidence against which to check the results of this study at one or two points for reasonableness.

Fortunately, we have never had a large nuclear war and it is devoutly to be hoped that we never will. However, there are two natural phenomena that can rival nuclear war in at least energy release: volcanoes and asteroid impacts.

Volcanoes

The most violent volcanic eruption in historical times was the Tambora eruption in what is now Indonesia, in April of 1815. The series of explosions accompanying the eruption are estimated to have ejected from 140 to 200 cubic kilometers of dust, some small fraction of which got into the stratosphere. It is argued with some justification that the very cold summer of 1816 was a consequence of this eruption. (Stommel, 1979).

That summer was the coldest on record for the northeastern United States and at least one location in central Europe. However, it was not the coldest for many other locations, particularly in eastern Europe. (Landsberg, 1974).

Volcanic aerosol clouds are not a good analogy to nuclear dust clouds in that their average particle size is too large and the particle density is so great that the cloud density overcomes its buoyancy. Only a very small fraction of the fine particles in the dust reach the stratosphere, much smaller than that from nuclear weapons. Furthermore, the worldwide temperature decreases which have been ascribed to volcanic eruptions, (a few tenths of a degree centigrade) (La March et al, 1984) are ascribed by some authorities to aerosols of sulfuric acid produced from the sulphur dioxide gas emitted by the volcano. (Hansen et al, 1980). It may be possible to argue that the volcanic dust which has been observed cannot be shown to be responsible for the worldwide temperature decreases which have been observed. However, some species extinctions in the paleontological past are believed to be coincident with much more massive events, and a cataclysmic climatic change due to

volcanism cannot be ruled out.

Asteroid Impact

As mentioned earlier, large-scale species extinction took place approximately 65 million years ago to define the Cretaceous-Tertiary discontinuity. A layer of clay abnormally high in iridium was discovered in a stratum corresponding to this age in many places over the world. It was postulated by Louis Alvarez and others (Alvarez et al, 1980) that the layer with abnormally high iridium content and the species extinction were due to the same event -- the impact of a meteor approximately 10 kilometers in diameter. If one assumes the meteor arrived with a relative velocity comparable to solar orbital velocity, 25 kilometers/second, and had a stony composition, one arrives at an impact energy of 10^8 megatons of TNT equivalent. This event had approximately 10,000 times the energy of some of the nuclear wars considered in the TTAPS study.

In a separate paper, four of the same TTAPS authors have applied their computational methods to the asteroid impact (Pollack et al, 1983). They calculated temperature depression curves which are very similar to those calculated for nuclear war. The temperature minimum occurs later, 120-180 days, but the temperatures still have largely recovered at the end of a year.

That the same minimum temperatures are reached in the Nuclear Winter and the asteroid impact is perhaps not surprising. Once the absorbing layer of the atmospheric dust has cooled to the black body temperature necessary to balance the heat input from the sun, the temperature of the surface will tend toward the same temperature. That both systems approximately recover in a year is somewhat surprising. The TTAPS authors explain the rapid recovery in the case of the asteroid impact by the assumption that, with the very high particle density, coagulation followed by sedimentation becomes an important removal mechanism. This mechanism is assumed not to operate in a Nuclear Winter case due to the much more dilute nature of the stratospheric particulate matter. In an earlier version of their paper, the authors had a 25,000-megaton worst case, assuming a finer particle size and somewhat

more smoke. This case had a 65 centigrade degree temperature depression, as well as an unusually slow recovery, even after a year. It was far more severe than the postulated asteroid impact. We find this particular result unreasonable.

The Cretaceous-Tertiary (KT) event is important in that it provides evidence that (1) cataclysms possibly with some similarities to nuclear war, can cause severe environmental effects destructive to life, but (2) not so severe that all life is destroyed. The latter point is important because it indicates that the consequences of an event several orders of magnitude larger in energy release than a nuclear war, although very widespread, were finite in severity.

Recent analysis of species extinctions and large ancient impact craters suggests that the KT event is far from unique. The evidence suggests such events involving more than one large impact occur periodically every 26 to 28 million years, most recently 13 million years ago. (Science and the Citizen, 1984).

It must be noted that the KT species extinction does not confirm the cooling effect associated with nuclear winter. The observed species extinction could have been caused by the interruption of photosynthesis at any temperature.

SIGNIFICANCE

There are large aggregate uncertainties in the results of these calculations. They indicate only qualitative results that there will probably be a cooling effect and for sufficiently severe scenarios, and the cooling could be significant. Past experience with calculations of major environmental impacts of technological activities (e.g., the supersonic transport) has been that the initial calculations usually over-estimate the magnitude of the effect. The calculations are a strong indication that a vigorous effort in scientific research is merited on this subject. However, uncertainties are so large that it is far too soon to contemplate any policy actions based on the prospect of this phenomenon.

It should be pointed out that a calculated hemispheric temperature depression of a few degrees represents an average over the entire

hemisphere for the time interval considered. It is an artifact of the one-dimensional mathematical model used to make the calculations tractable. In real world, temperature variations will be much larger for short periods of time over small areas. In the famous summer of 1816, "the year without a summer", the calculated average temperature depression was on the order of six-tenths of a centigrade degree. But in portions of New England, snow storms were experienced in June and frosts in August. (Strommel, 1979). Larger average temperature depressions are manifested not only by larger areas of abnormally low temperature lasting for longer periods of time, but also larger maximum temperature excursions. The important point to remember is that one hard frost in the middle of a growing season can cause a total crop failure, and period of cool or cloudy weather can cause important reductions in yield.

The residual temperature depression after one year may be as important as the maximum temperature depression seen thirty days after the attack. For a number of not improbable scenarios, the TTAPS authors calculate long-term temperature depressions which extrapolate to several degrees at one year after the attack. The loss of a single crop year caused by the early temperature depression is not a new possible consequence of nuclear war for either the United States or the Soviet Union. Both are facing the loss of a crop year without Nuclear Winter, due to fallout, and both are estimated to have approximately a year's supply of grain stored. In the Soviet Union, this is in the form of state-held strategic grain reserves, and in the United States, it is generally stored on farms or at trans-shipment points in farming areas. Of course, loss of the first crop year would be catastrophic to nations without a year's supply of stored food.

However, a hemispheric depression of several degrees at the end of one year after the attack could imply loss of a second crop year. It is believed that neither the United States nor the Soviet Union presently has enough food stored to handle this contingency unless their population losses in the nuclear exchange approach 50%.

Should the United States decide to maintain an additional year's supply of food for whatever reason (agricultural price stabilization,

precaution against famine in less-developed countries, etc), the purchase price of the approximately 70 million tons of the least expensive grain, corn, would cost approximately 5 billion dollars at current prices. The inclusion of more expensive grains for nutritional balance, plus handling, packaging, shipping, and storage could more than double this cost.

Strategic Implications

The extremely low temperatures predicted in some nuclear winter scenarios could provide an additional complication to civil defense planning, especially in the part of the U.S. accustomed to mild winters. However, fallout presents a far more difficult problem, and some measures taken against it (earth shielding, crowding) also provide some protection against low temperatures. Maximum use of available winter clothing and improvised cold weather clothing (Kearny, 1979) can provide great protection against hypothermia.

The major difficulty presented by nuclear winter to survivors of a nuclear war may be its effect on water supplies. Extreme cold can freeze water supply system equipment. Recharge of ground water supplies does not occur during very cold weather. The other atmospheric changes postulated for nuclear winter can be expected to disrupt rainfall patterns, affecting those areas dependent on surface water supplies.

The Soviet Union is approximately 20° in latitude further north than corresponding areas of the United States. Partly as a result of this climate and partly due to organizational deficiencies, the Soviets experience chronic difficulties in meeting their agricultural production goals in peacetime with an undamaged industrial support system. If Nuclear Winter on subsequent examination turns out to have a high probability as a consequence of nuclear war, it can be expected to fall especially hard on the higher latitude areas of the Soviet Union. One could have a situation, after a year, of reduced production in the United States and no production at all in the Soviet Union.

Canada would experience the same climatological change as the Soviet Union. However, Canadian agriculture is far more competent than that of the Soviet Union, producing multiples of its minimum nutritional requirements for a large export traffic. As in the United States, most of

the year one could expect large amounts of grain in storage, more than enough to meet the survival requirements of the Canadian population for one or two lost crop years.

If the effect of smoke turns out to be as important as the TTAPS model indicates, attacks on cities with the present design of nuclear weapons will be severely deterred. Refined calculations may identify a threshold beyond which further attacks on cities begin to produce climatological effects and, as noted earlier, this threshold could be lower for the Soviet Union than for the United States.

It is possible to design earth-penetrating nuclear weapons which would produce little or no incendiary effects. These weapons will have far less yield for a given payload, due to the strong structure required to survive penetration into the earth. One would also expect a much reduced cloud stabilization height and possibly even reduced amounts of fallout outside the immediate area of the crater.

If stratospheric dust turns out to be as important as the TTAPS calculations suggest, especially at long times, there will be an incentive to airburst most of the megaton range weapons with a corresponding reduction in fallout. To avoid dust in the stratosphere, surface bursts must be restricted to approximately 100 kilotons. This would significantly reduce fallout anticipated from a large attack. It should be noted that there are large numbers of 40-kiloton and 100-kiloton warheads in the U.S. arsenal. The Soviet strategic arsenal is believed to consist predominantly of weapons of much higher yield -- near-megaton to multimegaton.

Caveat

We have discussed here what we presently believe to be the principal sources of uncertainty affecting the magnitude and duration of the cooling in a Nuclear Winter. However, we recognize that it is entirely possible, in this rather brief review, that we have overlooked something of first importance, something that could significantly alter the results.

It may be noted that the very extensive sensitivity studies carried out by TTAPS (and mainly reported in the longer articles, eg., Turco et al 1983b) deal primarily with uncertainties in the source terms, i.e., the quantities of dust and soot and the physical characteristics of the dust. Only the "slow-rainout" sensitivity case touches on the behavior and consequences of the injected aerosols. While there are undoubtedly major uncertainties in the source terms, we believe that the behavior of the aerosols, once injected, and the highly non-linear response of the atmosphere to the very large perturbations imposed on it are equally important sources of uncertainty.

It should also be noted that the foregoing review has dealt almost entirely with the question of surface temperature. It may well be that changes in precipitation would prove to be equally important. Understandably, this issue, though recognized, is not analyzed in the TTAPS study, because of limitations of the one-dimensional radiation-convection models. Even the three-dimensional General Circulation Models have far more difficulty with precipitation patterns than with temperatures. Even if the temperature reductions following a nuclear war prove to be much less than indicated by the TTAPS study, there could still be very severe damage to crops by drought in regions normally dependent on adequate rainfall. Resolution of this and related questions, like that of temperature, will require much further work.

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A PRELIMINARY REVIEW OF THE TTAPS
NUCLEAR WINTER SCENARIOS

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ABSTRACT

We have reviewed the paper "Global Atmospheric Consequences of Nuclear War" by R. P. Turco, O. B. Toon, T. P. Ackerman, J. B. Pollack and C. Sagan (TTAPS). On the basis of assumptions on the smoke and dust produced by a massive nuclear attack on the cities in the northern hemisphere, and calculations using a one-dimensional radiation-convection model of the atmosphere, the TTAPS authors postulate severe temporary climatological consequences of the attack. The consequences, popularly referred to as "Nuclear Winter", include absorption of most sunlight by atmospheric aerosols and surface cooling for several weeks on the continental land masses to temperatures as low as -25°C in the summer.

We did not have access to their model and have not checked their calculations. Their assumptions about dust from groundbursts are consistent with the best data available. Their assumptions concerning smoke produced by urban fires, which are critical to their results, and wild fires are questionable. They have ignored the effects of masonry rubble on the combustibility of cities, and the lack of vegetation around most U.S. strategic targets.

There are huge uncertainties in the results postulated by this paper, in part from the factors above, from the one-dimensional calculation, the effects of the oceans, and the rate of removal of the aerosols. We conclude that some cooling is likely but that it would probably be smaller rather than larger than calculated. It is much too soon to contemplate any policy or strategy changes based on these results. If subsequent more careful calculations confirm these results, they will provide incentives for strategic nuclear offensive forces of both the U.S. and Soviet Union to reduce weapon sizes, avoid surface bursts and city attacks, and deploy earth-penetrating weapons. These incentives will be stronger for the Soviet Union which is at higher latitudes and has a more marginal agriculture.

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